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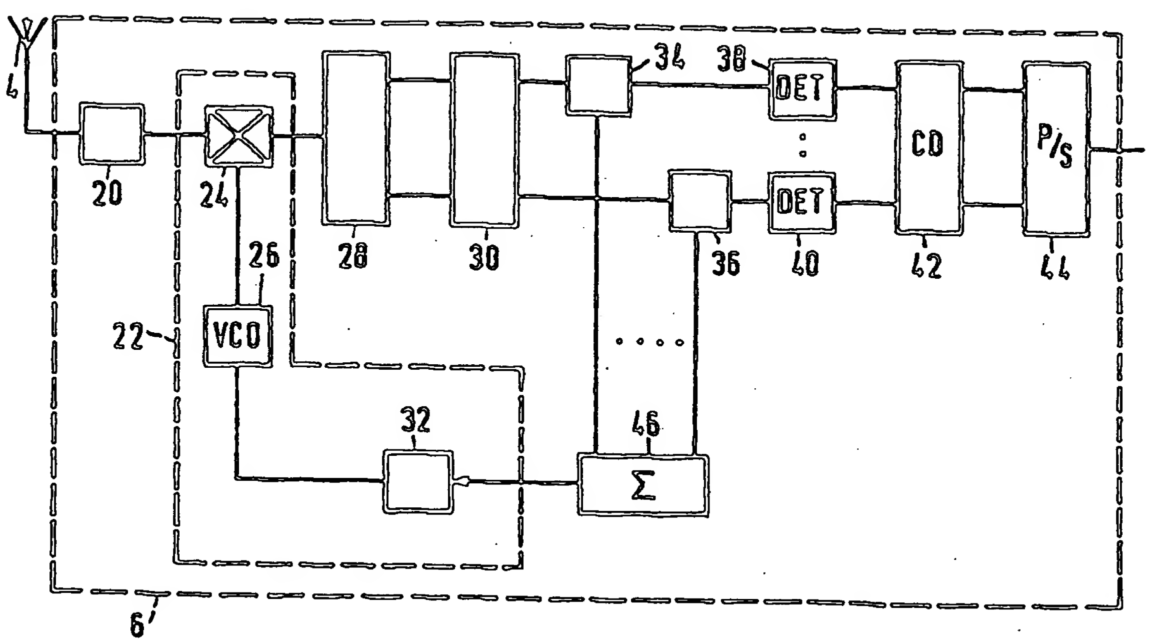

(57) Abstract

In an OFDM transmission system it is required to correct phase error in the received signal in order to be able to recover the transmitted symbols. In order to obtain an accurate phase correction the phase errors of separate carriers are determined by separate phase error measuring means (34...36) and combined in combining means (46). The combined phase error signal is used to control phase correction means (22) comprising a loop filter (32) and a controllable oscillator (26), in order to correct a phase error common for a plurality of carriers.

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"Digital transmission system"

The invention is related to digital transmission systems using a multiple carrier signal comprising a multiple of carriers modulated by digital symbols. The invention is also related to a receiver for receiving such multiple carrier signals.

Such a system is known from the paper "Analysis and simulation of a Digital Mobile Channel Using Orthogonal Frequency division multiplexing" by L.J. Cimini in IEEE Transaction on Communications, Vol. COM-33, No. 7, July 1985.

In transmission of digital signal over radio signals several transmission impairments have to dealt with. A first impairment is so called multi-path transmission, which is caused by transmission of a signal from a transmitter to a receiver via one direct path and via one or more indirect paths due to reflection of the transmitted signal by buildings or other structures. In digital transmission multi-path transmission results into intersymbol interference. A further impairment which is a consequence of multipath propagation is frequency selective fading. This means that fading can occur which heavily depends on the frequency of the signal to be transmitted. With increasing symbol rates the adverse effect of the previously mentioned impairments becomes more manifest.

Important improvements with respect to the vulnerability to the above mentioned impairments can be obtained by using a multiple carrier signal comprising a multiple of carriers, at least a part of them being modulated with the digital symbols to be transmitted. A sequence of symbols having a first symbol rate is subdivided into N parallel sequences of symbols having a second symbol rate being a factor N lower than the first symbol rate. Said N sequences of symbols are modulated on N carriers. In the receiver these N carriers are demodulated, and decisions about the values of the received symbols are made. The N received sequences of symbols can be combined to one single sequence of output symbols.

Due to the reduction of the transmission rate of each sequence of symbols the influence of intersymbol interference due to multi-path propagation is decreased accordingly.

To be able to demodulate the modulated carriers correctly, it is needed that the frequency and a reference phase of the modulated carriers transmitted is exactly known. In the prior art system the frequency and reference phase of the modulated carriers is

derived from two pilot signals added to the modulated carriers at the transmitter. Said pilot signals have an accurate known frequency. In the receiver the pilot signals are extracted from the received signal, and a phase correction signal is derived from them to control phase correction means for correcting the phase of the received multi-carrier signal.

In the prior art receiver the phase correction depends on the correct reception of the pilot signals. If one of the pilot signals disappears eg. due to a deep frequency selective fade the phase correction cannot take place correctly.

It is an object of the invention to provide a digital multiple carrier transmission system in which phase correction is more robust than in the prior art transmission system.

Therefor the invention provides a digital transmission system comprising a transmitter for generating a multiple carrier signal comprising a multiple of carriers modulated by digital symbols to be transmitted, a channel for transmitting said signal from the transmitter to a receiver, said receiver comprising phase correction means for deriving a phase corrected multiple carrier signal from a received multiple carrier signal in response to a phase control signal, demodulation means for deriving demodulated signals from said modulated carriers in the phase corrected multiple carrier signal, phase error measuring means for deriving phase error signals each representative for a phase difference of a phase of a received modulated carrier and a reference phase, and combining means for deriving said phase control signal by combination of said phase error signals.

The invention is based on the recognition that in the prior art transmission system the phase correction signal is derived from a portion of the complete signal representing only a fraction of the energy of the complete signal. This leads to an increased vulnerability to impaired transmission conditions. In the transmission system according to the invention the phase error signals of a large number of carriers are combined to obtain the phase control signal, thereby reducing the vulnerability to transmission impairments.

In an embodiment of the invention said phase correction means comprise an oscillator controllable by the phase control signal, and frequency conversion means for deriving the phase corrected multiple carrier signal from the received multiple carrier signal using an output signal of said oscillator. In this embodiment the correction of a phase error common to all carriers is combined with frequency (down)conversion. Such common phase error can be caused by a frequency offset between transmitter and receiver. Such frequency

offset results into cross talk between signals modulated on different carriers.

In a further embodiment of the invention said receiver comprises phase control loops for deriving said reference phases from said modulated carriers, the phase error measuring means are arranged for deriving said phase error signals from said phase control loops. The use of a phase control loop for determining the phase error signal for the different modulated carriers results in a accurate determination of the phase error in common for the modulated carriers. It is observed that a common phase error signal for the carriers is likely the result from a frequency deviation between the expected frequency of the received signal and the actual frequency of the received signal.

In a further embodiment of the invention the phase correction means, the demodulation means and the phase error measuring means constitute a further phase control loop having a low-pass transfer function. According to these measures the receiver is able to track automatically slow frequency variations common to all carriers.

In a preferred embodiment of the invention said phase control loops have a band-pass transfer function. By giving said phase control loops a band-pass transfer function, it is avoided that the phase control loops and the further phase control loop try to compensate the same phase error. This may result in a drift of the phase control signal beyond its bounds.

The invention will now be explained with reference to the drawings. Herein shows:

Fig. 1 a transmitter for a transmission system according to the invention;

Fig. 2 a receiver for a transmission system according to the invention;

Fig. 3 channel estimation means for use in the receiver according to Fig. 2;

Fig. 4 a first embodiment of phase error measuring means for use in the channel estimation means according to Fig. 3;

Fig. 5 a second embodiment of phase error measuring means for use in the channel estimation means according to Fig. 3;

Fig. 6 an embodiment of the controllable oscillator in the phase error measuring means.

In the transmitter according to Fig. 1 a digital signal to be transmitted is

applied to a series-parallel converter 8. N outputs of the series-parallel converter 8 are connected to corresponding inputs of a channel coder 10. N outputs of the channel coder 10 are connected to N inputs of an OFDM (Orthogonal Frequency Division Multiplex) modulator, being here a Inverse Fast Fourier Transformer 12. N outputs of the Inverse Fast Fourier transformer 12 are connected to inputs of a parallel-series converter 14. An output of the parallel-series converter 14 is connected to a first input of a mixer 16. An output of an oscillator 18 is connected to a second input of said mixer 16. The output of the mixer 16 is (eventually via a power amplifier) coupled to a transmitting antenna 3.

The sequence of symbols to be transmitted at the input of the transmitter 2 is converted by the series-parallel converter 8 into N sequences of symbols. These N sequences of symbols have a symbol rate which is a factor N lower than the data rate of the sequence of symbols at the input of the transmitter 1. In the channel coder 10 the N sequences of symbols are encoded using an error correcting code. A concatenated coding scheme has proven to be very effective. In this concatenated modulation scheme the outer code is a Reed Solomon code. The inner convolutional code is combined with modulation using the principle of set partitioning. At the outputs of the channel coder 10 signals defining the point of the constellation to be transmitted are available. The Inverse Fast Fourier Transformer 12 derives a block of N samples of a signal representing N carriers modulated with the N signals applied at its inputs. The parallel series converter 14 transforms the parallel block of samples into a sequence of signal samples constituting the OFDM signal. The output signal of the parallel-series converter 14 is converted by the mixer 16 to a desired RF frequency defined by the oscillator 18. The output signal of the mixer 16 is radiated by the transmitting antenna 3.

In Fig. 2 the output of a receiving antenna 4 is connected to an input of a receiver 6. The input of the receiver 6 is connected to a front-end 20. The output of the front-end 20 is connected to an input of the phase correcting means 22. The phase correction means 22 comprise an oscillator 32 having an output connected to a first input of frequency conversion means 24. The input of the phase correction means, carrying the received multiple carrier signal, is connected to a second input of the frequency conversion means.

The output of the phase correction means 22, carrying the phase corrected multiple carrier signal, is connected to a series-parallel converter 28. N outputs of the series-parallel converter 28 are connected to N inputs of the demodulation means, being here a Fast Fourier Transformer 30. N outputs of the Fast Fourier Transformer 30 are connected to corresponding channel estimation means 34 · · · 36. A first output of each of

the channel estimation means 34 ··· 36 is connected to an input of combining means 46. The output of the combining means 46 carrying the phase control signal, is connected to an input of the phase control means 22. Said input is coupled to a control input of the controllable oscillator 26 via a filter 32.

A second output of the channel estimation means 34 ··· 36, carrying a phase corrected modulated carrier, is connected to an input of a corresponding detector 38 ··· 40. N outputs of the detectors 38 ··· 40 are connected to N inputs of a channel decoder 42. The outputs of the channel decoder 42 are connecter to a corresponding input of a parallel-series converter 44. At the output of the parallel-series converter 44 the received digital signal is available.

An OFDM signal received by the antenna 4 is processed by the front-end 20, and in most cases converted from the original RF frequency to a lower IF frequency. Further the IF signal is sampled and converted into a digital signal by an analog to digital converter. The output signal of the front-end 20 is again down converted in frequency and phase corrected by means of the combination of the frequency conversion means 24 and the controllable oscillator 26. This frequency conversion may take place by multiplying the complex samples at the output of the front-end by a factor $e^{j\Delta\phi(t)}$. This factor is generated by the (digital) controllable oscillator 26. In the series-parallel converter 28 the phase corrected samples of the multiple carrier signal at the output of the phase correction means 22 is converted into blocks of N samples. In the Fourier Transformer 30 the output signal of the series-parallel converter 28 is converted into N (in general complex) Fourier coefficients. The channel estimation means 34 ··· 36 comprise the phase measuring means which determine for each of the Fourier coefficients at the outputs of the Fast Fourier transformer 30 a phase error signal being representative of the difference of the phase of said Fourier coefficient and a reference phase. The phase error signals from all phase error measuring means are combined by the combining means. Preferably the phase error signals are weighted with an estimation of the signal to noise ratio of the corresponding carrier. This signal to noise ratio is also determined by the phase error determining means 34 ··· 36. By weighting the phase error signals with the corresponding signal to noise ratio a more reliable phase control signal can be obtained. It is observed that other ways of combining the individual phase error signals e.g. unweighed adding of the phase error signals can be used in the receiver according to the invention. The phase control signal is a measure for the phase error in common for all carriers of the OFDM signals which can have individually rather different phase errors due to frequency selective fading. The filter 32 has a first order

low pass transfer function, resulting in a second order phase locked loop. The parameters of said second order phase locked loop can be determined according to well known design principles. The phase error measuring means 34 ··· 36 also determine demodulated signals in which the individual phase error in the corresponding carrier has been corrected. The detectors 38 ··· 40 derive detected digital symbols from the phase corrected output signals of the phase error measuring means. If coherent detection is used, a carrier signal generated in the phase error measuring means has also to be applied to the detectors 38 ··· 40. The channel decoder 42 performs error correction for the output symbols available at the output of the detectors 38 ··· 40. The N output symbols of the channel decoder 42 are converted into a single sequence of digital symbols by the parallel-series converter 44.

The input of the channel estimator according to Fig. 3 is connected to a noise power estimator 50, a total power estimator 52 and phase error measuring means 54. Further the input signal of the channel estimator is connected to an input of a multiplier 60. The output of the noise power estimator, carrying a signal which is representative for the noise power in the input signal is connected to a first input of a divider circuit 56. The output of the total power estimator, carrying a signal which is representative for the total power of the input signal, is connected to a second input of the divider circuit 56, and to an input of a calculation circuit 58. An output of the phase error measuring means 54, carrying an output signal which is representative for the phase shift of the channel, is connected to a second input of the calculation circuit 58, and to a first input of a multiplier 62. An output of the divider circuit 56 is connected to a second input of the multiplier 62. The output of the multiplier 62 constitutes the first output of the channel estimation means. The output of the multiplier 60 constitutes the second output of the channel estimation means.

The total power estimator 52 determines a measure for the total power of the input signal in a recursive way. The power measure $|\alpha_k|^2$ can determined according:

$$|\alpha_k|^2 = \mu_\alpha |\alpha_{k-1}|^2 + (1-\mu_\alpha)\,|r_k|^2 \tag{1}$$

In (1) is r_k the complex valued input sample of the phase estimation means 34 at sample instant k and is μ_α a constant defining the time constant of the recursive process for determining the power measure $|\alpha_k|^2$. The noise power in the input signal is determined by calculating the spread of the power of the input signal. This is especially useful for transmitted signals having a constant amplitude such as FSK and PSK signals. This spread σ_k^2 can be determined according to:

An estimate γ_k of the signal to noise ratio can be determined by the dividing circuit 56 from:

$$\sigma_k^2 = \mu_\sigma \sigma_{k-1}^2 + (1-\mu_\sigma)\left(|r_k|^2 - |\alpha_k|^2\right)^2 \tag{2}$$

$$\gamma_k = \frac{|\alpha_k|^2}{\sqrt{\sigma_k^2}} \tag{3}$$

The phase error determined by the phase error measuring means 54 is multiplied by γ_k on order to obtain a phase error signal weighted with the signal to noise ratio.
In the calculation circuit 58 an estimate of the inverse of the complex value of the transfer function of the channel is calculated This estimation is equal to:

$$\frac{1}{H} = \frac{e^{-\phi_e}}{\alpha_k} \tag{4}$$

The signal r_k is multiplied by 1/H by the multiplier 60 to obtain a detection signal of correct amplitude and phase.

In the phase error measuring means 54 the input signal r is applied to an input of a quadrupler 70. The output of the quadrupler 70 is connected to a first input of a phase detector 72. The output of the phase detector 72 is connected to the input of a loop filter 74. The output of the loop filter 74 is connected to a control input of a controllable oscillator 76. The output of the controllable oscillator 76 is connected to a second input of the phase detector 72 and to an input of a frequency divider 78.

The phase error measuring means 54 according to Fig. 5 is intended for measuring the phase error for Quadrature Phase Shift Keyed signals. The quadrupler 70 derives a signal having a frequency equal to four times the frequency of the signal r. Furthermore the modulation of the signal r has been removed by the quadrupling operation. The phase detector 72, the loop filter 74 and the controllable oscillator 76 constitute a phase locked loop. For the reasons mentioned above the transfer function of the combination of the loop filter 76 and the controllable oscillator 76 is chosen to obtain a phase locked loop having a band-pass transfer function. The transfer function H_l of the loop filter 74 is chosen equal to:

$$H_l = K_p + \frac{K_i}{Z-\mu}$$

In (5) K_p,K_i and μ are constants, and Z^{-1} is the delay operator over one sampling interval. The transfer function H_{osc} of the controllable oscillator 76 is equal to:

$$H_{osc} = \frac{1}{Z-\mu} \tag{6}$$

The implementation of a controllable oscillator having the transfer function according to (6) is explained later. The above mentioned choice of transfer functions H_l and H_{osc} leads to a second order phase locked loop having a band-pass transfer function. It has to be ensured that the cut off frequency of the phase locked loop according to Fig. 2 for correcting the common phase error is lower than the lower edge of the pass band of the phase locked loop according to Fig. 4. The frequency divider 78 derives a signal having the same frequency as the modulated carrier from the output of the controllable oscillator. The control signal C is needed to resolve the phase ambiguity introduced by the quadrupling operation. The phase ambiguity can be resolved by using reference symbols having a phase known at the receiver.

In the phase error measuring means according to Fig. 5 the input signal r is applied to a first input of a complex divider 82. the detected symbols $\hat{a}_k$ are applied to an input of a remodulator 80. The output of the remodulator 80 is connected to a second input of the complex divider 82. The output signal of the complex divider 82 is connected to an argument calculator 84, an output of which is connected to an input of a loop filter 86. At the output of the argument calculator 84 the phase error signal is available The output of the loop filter 86 is connected to the output of the controllable oscillator.

The remodulator 80 reconstructs on basis of detected symbols the modulated signal using the output signal of the controllable oscillator 88. The phase difference between the actual input signal and the reconstructed signal at the output of the remodulator 80 is a measure for the phase error. The output signal of the complex divider is a number having an argument being equal to the phase difference of r and the reconstructed modulated signal. This argument is determined by the argument calculator 86. The remaining elements of the phase error measuring means, being the loop filter and the controlled oscillator are equal to the corresponding elements in Fig. 4.

It is observed that it is possible to dispense with the quadrupler 70 in the phase error measuring means according to Fig. 4 or the remodulator 80 in the phase error measuring means according to Fig. 5. Therefor reference symbols having a known phase must be introduced into the received signal. Then it is possible to activate the phase error measuring means only during the presence of such a reference symbol. Then the (averaged) phase corresponding to said reference symbol is used as reference phase. The use of such reference symbols results in a reduction of the complexity of the phase error measuring

means.

In the controllable oscillator according to Fig. 6 the input is connected to a first input of an adder 90. The output of the adder is connected to an input of a delay element 92. The output of the delay element 92 is connected to an input of a modulo M converter 96, and to an input of a multiplier 94. A constant μ is applied to a second input of the multiplier 94. The output of the multiplier 94 is connected to the second input of the adder 90. The output of the modulo M converter is connected to the inputs of a cosine ROM 98 and a sine ROM 100. The output signals of the cosine ROM 98 and the sine ROM 100 constitute the outputs of the oscillator.

The adder 90, the delay element 92 and the multiplier 94 constitute a leaky integrator having a transfer function according to (6). The modulo M converter converts the output signal Θ of the delay element 92 into a signal having a value Θ modulo M. The output signal of the modulo M converter is used to address the sine ROM 98 and the cosine ROM 100, in order to generate a pair of quadrature signals at the output of said cosine ROM 98 and said sine ROM 100 respectively.

CLAIMS

1. Digital transmission system comprising a transmitter for generating a multiple carrier signal comprising a multiple of carriers modulated by digital symbols to be transmitted, a channel for transmitting said signal from the transmitter to a receiver, said receiver comprising phase correction means for deriving a phase corrected multiple carrier signal from a received multiple carrier signal in response to a phase control signal, demodulation means for deriving demodulated signals from said modulated carriers in the phase corrected multiple carrier signal, phase error measuring means for deriving phase error signals each representative for a phase difference of a phase of a received modulated carrier and a reference phase, and combining means for deriving said phase control signal by combination of said phase error signals.

2. Digital transmission system according to claim 1 wherein said phase correction means comprise an oscillator controllable by the phase control signal, and frequency conversion means for deriving the phase corrected multiple carrier signal from the received multiple carrier signal using an output signal of said oscillator.

3. Digital transmission system according to claim 1 or 2 wherein said receiver comprises phase control loops for deriving said reference phases from said modulated carriers, the phase error measuring means are arranged for deriving said phase error signals from said phase control loops.

4. Digital transmission system according to claim 3 wherein the phase correction means, the demodulation means and the phase error measuring means constitute a further phase control loop having a low-pass transfer function.

5. Digital transmission system according to claim 4 wherein said phase control loops have a band-pass transfer function.

6. Receiver for receiving a multiple carrier signal comprising a multiple of carriers modulated by digital symbols, said receiver comprising phase correction means for deriving a phase corrected multiple carrier signal from said multiple carrier signal in response to a phase control signal, demodulation means for deriving demodulated signals from said modulated carriers in the phase corrected multiple carrier signal, phase error measuring means for deriving phase error signals each representative for a phase difference of a phase of a received modulated carrier and a reference phase, and combining means for

deriving said phase control signal by combination of said phase error signals.

7. Receiver according to Claim 6 wherein said phase correction means comprise an oscillator controllable by the phase control signal, and frequency conversion means for deriving the phase corrected multiple carrier signal from the received multiple carrier signal using an output signal of said oscillator.

8. Receiver according to claim 6 or 7 wherein said receiver comprises phase control loops for deriving said reference phases from said modulated carriers, the phase error measuring means are arranged for deriving said phase error signals from said phase control loops.

9. Receiver according to claim 8 wherein the phase correction means, the demodulation means and the phase error measuring means constitute a further phase control loop having a low-pass transfer function.

10. Receiver according to claim 9 wherein said phase control loops have a band-pass transfer function.

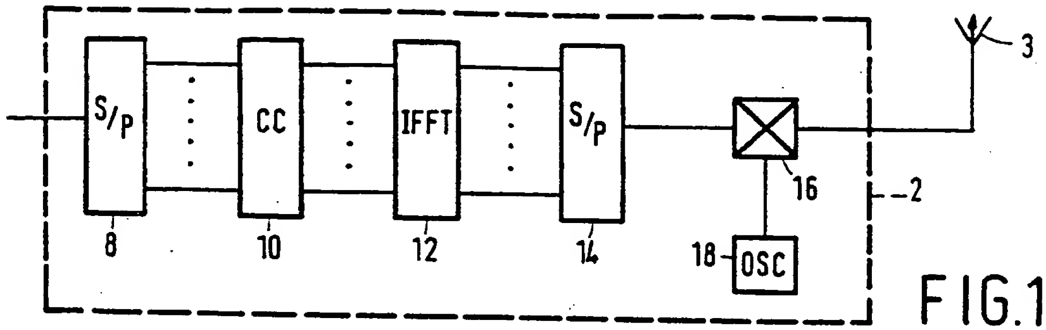

FIG.1

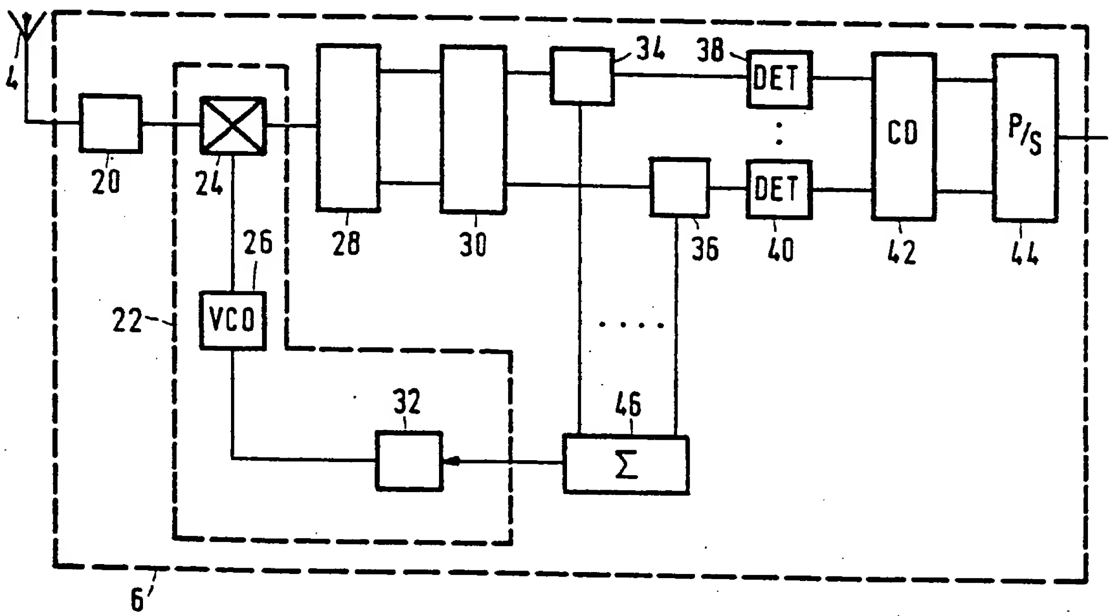

FIG.2

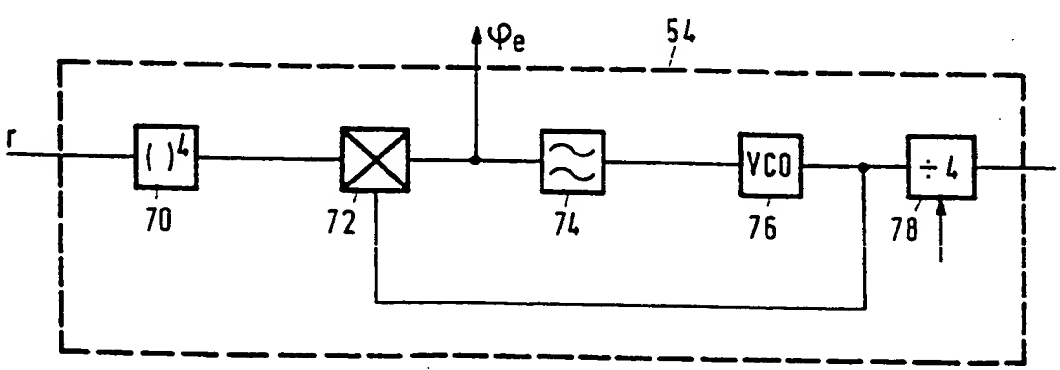

FIG.4

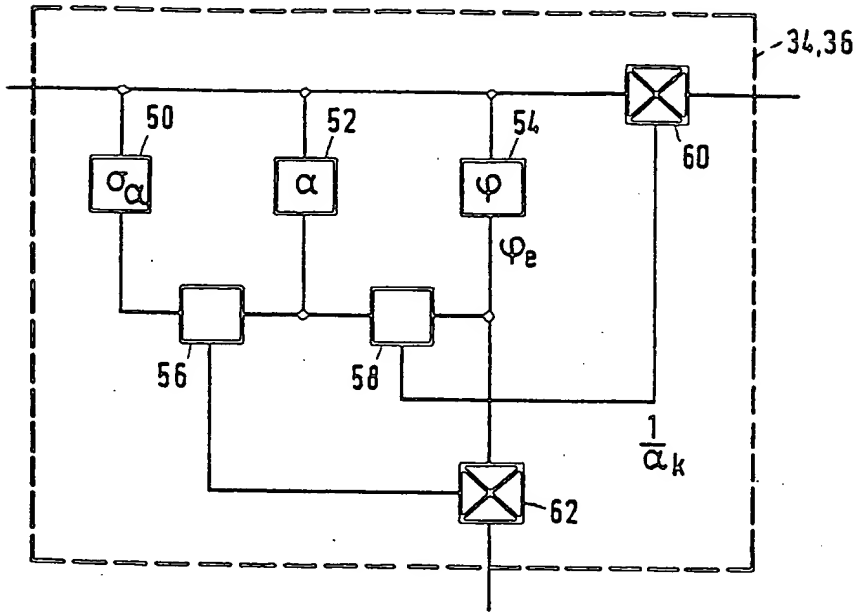

FIG.3

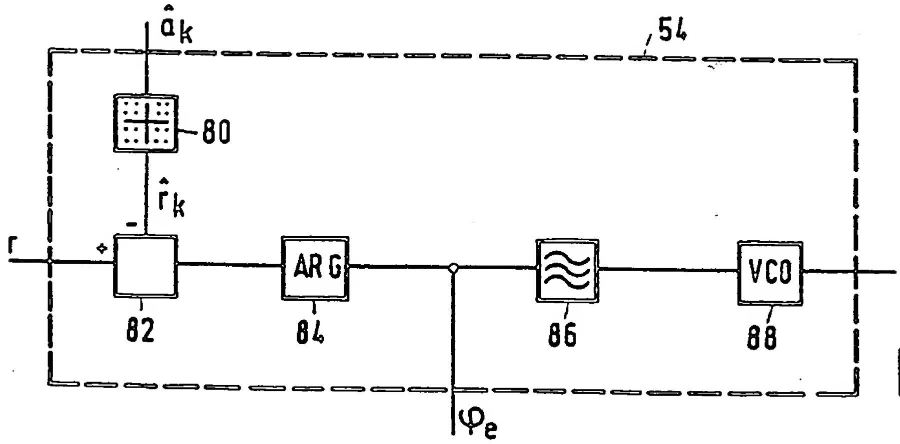

FIG.5

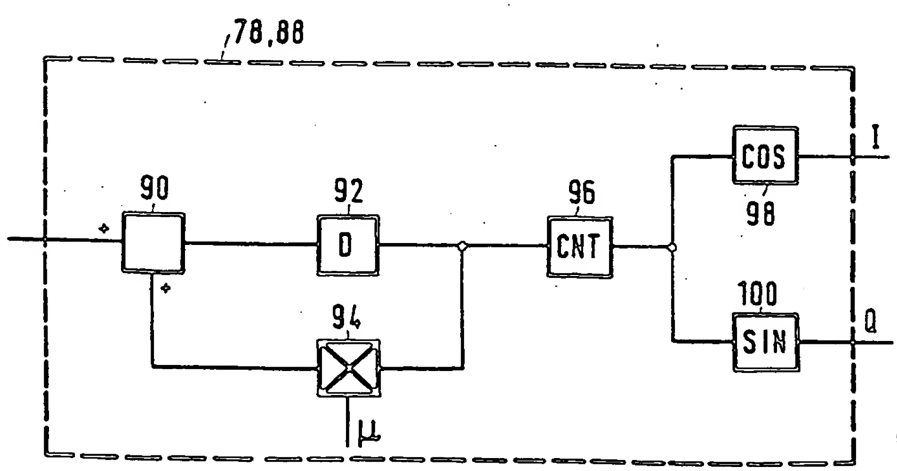

FIG.6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB 95/00046

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: H04L 5/06, H04J 11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: H04J, H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, CLAIMS, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	WO, A1, 9205646 (NATIONAL TRANSCOMMUNICATION LIMITED), 2 April 1992 (02.04.92), page 9, line 1 - page 10, line 11; page 21, line 13 - page 22, line 18; page 28, line 1 - page 29, line 16 --	1,6
A	IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, Volume 42, No 3, August 1993, WILLIAM D. WARNER ET AL, "OFDM/FM Frame Synchronization for Mobile Radio Data Communication", page 302 - page 313, see page 304 - page 307 --	1,6

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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INTERNATIONAL SEARCH REPORT

International application No.
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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	IEEE TRANSACTIONS ON COMMUNICATIONS, Volume 33, No 7, July 1985, LEONARD J. CIMINI, JR, "Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing", page 665, see whole document; cited in the application --	1,6
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INTERNATIONAL SEARCH REPORT
Information on patent family members

01/04/95

International application No.
PCT/IB 95/00046

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		WO-A-	9115925	17/10/91
WO-A1- 9426046	10/11/94	NONE		